IAC-04-I.4.08

FROM BUSES TO BODIES: SMART MATTER FOR SPACE SYSTEMS APPLICATIONS

Michael L. Rilee
L-3 Communications GSI, Largo, Maryland USA
Michael.Rilee@L-3com.com

Steven A. Curtis[□], Walt Truszkowski[□], Pamela E. Clark[†], and Cynthia Y. Cheung[□]
[□]NASA Goddard Space Flight Center, Greenbelt, Maryland USA
[†]L-3 Communications GSI, Largo, Maryland USA
Steven.A.Curtis@nasa.gov, Walt.Truszkowski@nasa.gov,
Pamela.E.Clark@gsfc.nasa.gov, and Cynthia.Y.Cheung@nasa.gov

ABSTRACT

Advances in micro- and nano-fabrication present to us the opportunity to reconsider how the very mechanical structure of a spacecraft may be implemented. These advances will be at least as important as the development of structural truss technology. A new mechanical architecture called Super Miniaturized Addressable Reconfigurable Technology (SMART) has been developed to guide the integration of sensing, actuation, and control in a new structural material. SMART matter is a massively parallel system of interconnecting reconfigurable nodes fabricated using macroscopic electromechanical systems (EMS), micro-electromechanical systems (MEMS), or nano-electromechanical systems (NEMS) as required by particular applications. This highly integrated three-dimensional mesh of actuators and structural elements is composed of nodes that are addressable as are pixels in an LCD screen. SMART matter is not susceptible to single-point failures and, via techniques such as patching or node-migration, SMART structures may heal after suffering damage or failure. Control of these massively parallel systems in the context of space mission requirements is discussed. SMART structures provide a way to tame the explosion of degrees of freedom implicit in the use of MEMS and NEMS devices for macroscopic structures.

FULL TEXT

INTRODUCTION

The design and manufacturing of spacecraft systems is at this point quite advanced. It is a mature field with standards, operating assembly lines, and nearly half-a-century of experience. Off-the-shelf systems are available, and where these don't match mission requirements, they can often be customized. In addition to this growing capability, government and industry strives to maintain the capacity for developing experimental and low-production, even one-off production.

These systems and standards have grown and developed within a particular envelope of constraints. These constraints, or from a different viewpoint requirements and resources, have led to the development of systems reliable enough to meet mission goals. The missions have involved interplanetary exploration, Earth observation, manned space flight, and weapon delivery, to name a few. There is also a feedback loop, namely that mission designers develop their mission concepts within an understanding of what spacecraft technologies can provide.

Spacecraft buses are designed to be light and strong and provide the physical and spatial structure that keeps other spacecraft systems in place and guard against the rigors of the launch environment. They must mate properly with their launcher or other carrier and their coupled dynamic response to noise, vibration, and even heating loads must not involve harmful resonances or other stresses that lead to system damage or failure. Once in space, the environment is different: quieter and more predictable in some ways but poses its own challenges. Thermal management is important. Free-flying spacecraft present attitude control problems that depend on the dynamics of the spacecraft bus. Mission requirements for attitude control, vibration damping, electromagnetic cleanliness, and more instruct spacecraft bus design. To this, add the requirements for the exploration of planetary surfaces, which is the central feature of the new Exploration Initiative of the United States.

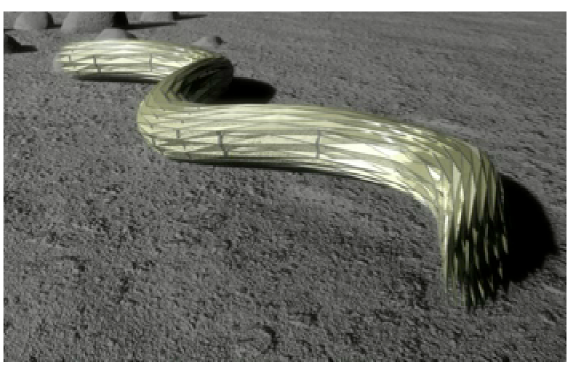

Figure 1. The Lander Amorphous Rover Antenna moves using Addressable Reconfigurable Technology.

Surface environments Sharing much with requirements for spacecraft systems, the requirements for systems for missions of planetary exploration encompass those previously mentioned. For the space-based component of planetary exploration systems many of the concerns are identical. For the ground-based or groundside systems important differences are brought to light that point towards new approaches. Happily, these new approaches can enable important new capabilities for the space side systems.

The key fundamental difference between the space environment and the planetary surface environment is that time and space are complicated and strongly coupled to your deployed system. From Apollo to the Mars Exploration Rovers great care has been taken in landing site selection because our capability to handle contingencies during the landing phase is extremely limited. Therefore, we choose what appear to be plain, safe, predictable locations in which to land. However, the fact that rocks, boulders, and other hazards do exist in these locations is a valid cause for anxiety during the last few minutes before word arrives from “Tranquility Base” or Gusev Crater.

It is ironic, that, for science missions at least, the very rocks that cause such consternation are the reason for the mission to begin with. Also, the reason behind developing rover technology is to provide the capability to move from the relative safety of the landing site to the relatively more dangerous locations of rocks, cliffs, fissures, and so on. Roving provides the ability to correct and improve the environment or situation of a deployed planetary mission system, i.e. a payload of scientific instruments. For systems that must deal with many degrees-of-freedom that are irregular, dynamic, or unknown, flexibility is the key: the ability to rove is one way to be flexible.

Flexible capabilities Spacecraft buses are known for their apparent rigidity and stiffness. These are remarkable because the systems are often very light, making use of advanced materials or structural forms to control their mechanical flexibility. However, there are many times when flexibility is required or at least allowable. Deployable systems, such as booms for magnetometers, antennae, power systems, or even parasols are important examples where degrees of freedom have been added to obtain important capabilities. Active, segmented reflectors for telescopes are a more recent development. Landing gear comes to mind as well. These extra degrees of freedom are introduced to gain flexibility to meet, say, the geometric constraints of fitting inside a launch or re-entry vehicle's shroud, or some system functional requirement such as distance from spacecraft electromagnetic interference or radioactive emissions.

Therefore, flexible degrees of freedom can add important flexibility to a system, but not without cost. Flexibility can work against you, providing avenues for unwanted increases in the entropy of your system. In other words, the increase in capability comes with a widening in the ways in which the system may fail. Deployable systems have become stuck, been too flexible, been not flexible enough, burned out their actuators, emptied their batteries, come loose during launch flailing other parts of the spacecraft, among other behaviors. Part of the reason for this trouble and the great impact it has on mission success is the single-string nature of the deployable system. Often full sub-system duplication is too expensive, and if one spring-loaded hinge is a problem, adding another may not help. Therefore, care is taken to make the simplest most reliable mechanically deployable system possible.

The role of control Part of the reason for this is control. Because current spacecraft are for the most part remotely commanded and programmed, the kinds of behaviors available to them have some important limits. Computer processing capacity on board these spacecraft is limited because radiation hardened or tolerant flight-capable computers are slower than groundside systems. Power and thermal limits also constrain computing capacity. Aside from important fail-safe capabilities, most spacecraft data processing is rightly characterized as command and data handling with processor capacity primarily maintaining data throughput between system and ground. When contingencies arise, the onboard system fails to a safe-mode. Most current spacecraft have neither the reflective capacity, the computing capacity, nor the smarts to detect, identify, and recover from such possibly complicated faults as those posed by deployable systems.

To summarize, compared to planetary groundside mobile systems, spacecraft have it easy: the physics and configuration of their environment is fairly well understood and systems with limited flexibility and adaptability can perform really well. For spacecraft there is generally a large separation of time scales: you have the time scales of the trajectory dynamics that are typically long compared to the time scales of the spacecraft and sub-systems themselves. There are critical periods where operations must occur as planned, but if problems arise, there can be plenty of time to recover. On the ground, there are objects and obstacles that make up the environment: these are close-by, largely uncontrolled, and affect moment-to-moment operations. The internal dynamics of a planetary rover may be fast, but interaction with the environment occurs in real-time unless great pains are taken selecting and operating within said environment.

BETTER BODIES

Our work builds on the research of the behavior-based school of robotic control.[1,2] Robotics researcher Mark Tilden once said that he sought to build "better bodies" not "better brains."[3] Current spacecraft systems are designed to operate within certain mission parameters and are designed to be commanded. In general, approaches to making these systems flexible and adaptable retain this foundation. Most approaches to making autonomous spacecraft take a deliberative approach sending commands to systems with tightly controlled degrees-of-freedom. When something goes awry, the control can help you determine what's wrong, or the system fails and literally disappears. For these systems, mission success requires control of as many variables as possible.

Behavior-based robots are built from the ground up to survive in uncertain environments, e.g. real-world groundside environments in real-time. To do this, something about them must be flexible enough to allow them to rapidly adapt within their environment while they still strive to achieve their mission goals. Instead of maintaining perfection all of the time, these systems are partners of the dynamic, the irregular, and imperfect. These systems continually strive to improve their situation, often without deliberate ratiocination or goal-driven action. The benefit of this approach is that these systems can show efficient, simple behaviors that are quite robust. A disadvantage is that these are not well directed towards high-level mission goals.

<u>A Synthetic Neural System for control</u> In other work, we have discussed a new control architecture that synthesizes these low- and high-level approaches. In this architecture behaviors and mission goals are brought together in Neural Basis Functions of a Synthetic Neural System.[1,2] This architecture is highly parallel, highly distributed providing memory, communications, and conflict resolution in a middleware layer that forms an Evolvable Neural Interface. Early versions of NBF systems run on single processors, but these SNS's are designed to be deployable onto networks of processors, including Beowulf cluster computers or Field-Programmable Processor Arrays.[4] The system is inherently scalable to massively parallel systems and would provide adaptable, flexible control for systems with many degrees of freedom.

ADDRESSABLE RECONFIGURABLE TEHCNOLOGY

<u>Addressability</u> On the other hand, multiple degrees of freedom need not be controlled by advanced techniques of automation. For situations where a relatively straightforward deployment is required a great deal of intelligence is not required. Addressability can be used to connect location and function to provide coordination for more regular behaviors. By regular behaviors, these can be simple deployments, reconfigurations, expansions, and the like.

<u>Reconfigurable structures</u> Which brings us to the reconfigurable technology we are developing, and provides the means to move beyond spacecraft buses to spacecraft bodies in the long term. In the nearer term, the new structural technology opens up a new highly configurable structural material that opens new possibilities for spacecraft systems and structural design.

<u>Nodes, struts, and trusses</u> We propose to go beyond current approaches to multi-functional and limited reconfigurability and control to a new structural material we apply to aerospace systems, but which in fact have a much broader application. The

fundamental element of this new material provides a degree of freedom to the material: it is a node and strut architecture that could be implemented in a number of different ways to suit many different mission requirements. A node provides power, communication, actuation, control, and flexibility. The struts couple nodes, certainly mechanically, but in some designs power and communication can involve the struts as well. Struts and nodes together form an interconnected network or truss, similar in concept to variable geometry trusses that have been studied in the past (Figure 2). The struts are generally reversibly extensible allowing inter-node separations to be changed. As these separations are changed the local configuration and when considered en masse the global configuration of the truss can be changed and controlled.

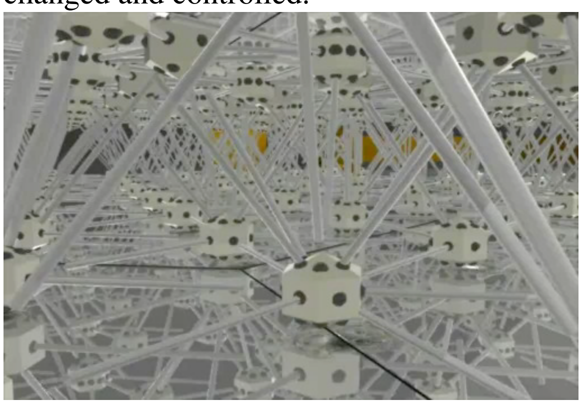

Figure 2. Nodes and struts together form ART & SMART trusses.

Shape control The shapes that can be obtained by trusses in general are quite broad. The finer the scale of the individual truss segments, the smoother and finer the features of the resulting global configuration. A reconfigurable truss allows many different configurations to be obtained by the same truss. Even the topology of the interconnections between struts and nodes need not remain fixed as reversible or irreversible fastening technologies may be deployed or embedded in these structures.

Controlling the shape of a truss concerns the designer of any variable geometry truss. Today the advance of computing technologies allows computing hardware and software to be distributed across multi-element systems as never before. However, for the nearest term systems developed with what we call Addressable Reconfigurable Technology (ART), the simplest forms of reconfigurability can be used. For example, the deployment of a frame to support a parasol or parabolic dish reflector can follow a fairly straightforward command pattern across the addressable array of actuators in the ART truss nodes. In such a case, the deployment of each actuator can readily be calculated before hand. Allowances must be made for feedback in case problems arise during deployment, however in these highly redundant systems, there is plenty of flexibility to reconfigure the truss structure to make up for problems.

Thus ART structures can follow predetermined patterns of command and reap the benefits reconfigurable trusses without requiring full autonomous control and solving anew the constraint requirements at every instant. The control can be fed as a predetermined sequence of commands distributed across the addressable network of nodes that drive the truss to the desired shape.

The ART architecture also provides a way for sophisticated central controllers to take advantage of the straightforward command patterns mentioned above.

For more advanced truss concepts, the computational power and sensing capability within the nodes allows these constraints to be maintained by the truss itself. In these concepts, the parallel computing system spread across the truss itself solves these constraints and takes on configurations in response to requirements or commands generated by a higher-level executive control agency of the system. We feel that this is the direction this work must go, because it is the only way that scales to the numbers of nodes and subsystems featured in systems implemented using nano-fabrication technologies.

Truss implementation Reconfigurable trusses can be implemented with a wide variety of technologies.[10] Variable geometry trusses have been implemented using hydraulic and other actuation schemes. At Goddard Space Flight Center, a Tetrahedral rover is being implemented using macroscopic electromechanical systems (EMS, e.g. Figure 3). As our ability to fabricate micro-electromechanical systems (MEMS) and nano-EMS (NEMS) improves, we will be able to construct trusses with elements of finer and finer length scales. With carbon nano-tube enhanced structural materials, multi-functional integrated logic and actuators, we expect that a structural material that essentially appears solid to the naked eye but which can attain a variety of shapes and sizes will become possible. Extremely Gossamer structures with integrated active shape control become possible with areal densities less than 1 - 10 grams per square meter are conceivable.

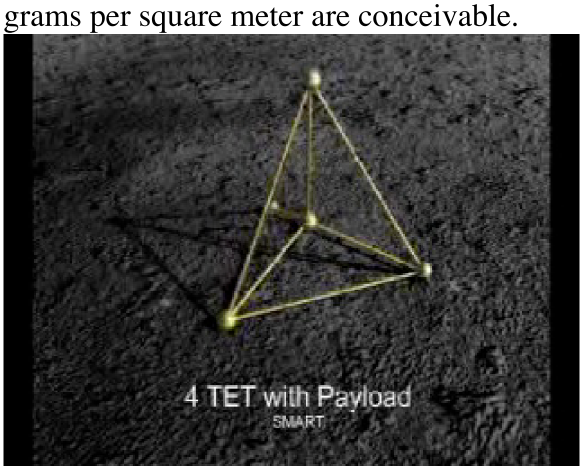

Figure 3. A Tetrahedral rover concept with a central payload node.

On the other hand, very robust systems are also possible, and may be realized today. As stated before, GSFC is currently developing rover prototypes based on this reconfigurable truss technology. The actuators and nodes could be made very robust. For example, if hydraulic technology used in modern construction equipment were applied, then highly flexible systems with lifting capacities of tons are readily conceivable. With existing EMS technology, large-scale systems can be deployed and reconfigured providing large packing factors, active control, and great adaptability.

Applications Thus a wide range of applications can be considered. Not only Gossamer structures for solar power or propulsion, but robust structures for construction or habitation on, say, the Moon are possible. A range of control options are possible, ranging from straightforward predetermined deployment in free space to more highly-variable reconfiguration that is contingent on real-time situations in a dynamic and irregular groundside environment. Furthermore, existing surface-based roving and structural technologies do not begin to address problems arising for robotic systems deployed in marine or subterranean environments. Robotic systems based on ART trusses provide new means for locomotion or manipulation, etc. Pseudopodia can be formed for locomotion and climbing. An example application is the Landing Amorphous Rover Antenna (LARA).[5]

Sample retrieval can be implemented by opening pockets in the truss and engulfing samples that are then be carried around within the structure. Components or subsystems can be embedded throughout the truss to provide the system with specific functions or capabilities: rocket propulsion systems, telemetry systems, drills, science instrument packages, and so on. ART trusses with different scale sizes could be mounted within the same system. For example, a large-scale robust truss could provide gross motion and locomotion whereas a finer scale truss for the dexterous manipulation of, say, samples or equipment. In addition, separate trusses can work together say to build larger structures, manipulate other items, or themselves, e.g. to scale obstacles that single systems alone could not surmount.

Fastening technologies coupled with radio homing mechanisms, perhaps based on Radio Frequency Identification (RFID) technology would allow the struts to attach and detach from the nodes.[6] This would allow individual nodes to attach to and detach from a truss. With appropriate actuation nodes could move about on a truss using ART to relocate themselves, "swinging" through the truss work. This could form the basis for ART truss construction or even self-repair as nodes, singly or as part of a sub-truss, could move to where they are needed and lock themselves into place. Though an advanced capability, the ability of nodes and truss segments, "patches," to move around or self-assemble is an extension of ongoing work on robotic assembly. In fact, much of ART systems is a synthesis of existing techniques and technologies with state-of-the-art capabilities for computation and communication.

ART trusses are variable geometry trusses with nodes that are addressable from a central controller. They are still parallel systems with computing, communication, sensing, and actuation distributed throughout their structure. As such, these systems can be implemented today. Computer modeling algorithms and high performance computers provide the means to control the many degrees of freedom of ART systems. Their redundancy provides flexibility and adaptability and opens up options for dealing with dynamic and irregular environments. For applications in more controlled situations, ART trusses provide a new approach to deployable systems or for systems that would benefit from highly variable geometries.

<u>Transition to continuum: SMART</u> The advance of micro- and nano-fabrication technologies provides the most exciting possibilities for the ART architecture. As individual nodes and struts become small and eventually microscopic, the ART truss itself will become indistinguishable from continuous matter. Super Miniaturized Addressable Reconfigurable Technology (SMART) is a step on the path towards the development of such articulate matter.[6-9] For the Revolutionary Aerospace Systems Concepts (RASC) program, a SMART truss was determined to have the characteristics needed for high performance solar sail propulsion for spacecraft of the Prospecting Asteroids Mission (PAM).

<u>Multi-level systems</u> A PAM solar sail truss would contain thousands of SMART nodes, more advanced structural concepts would contain even more. Conventional command and control of individual degrees of freedom do not scale to such systems. Neural control systems with local communications are a way to manage this complexity. Simple autonomic local controls can provide low-level behaviors including health and safety functions at the node or sub-truss level. Higher-level, goal-based control by deliberative heuristic systems can be coupled to and drive these low-level behaviors. In this limit, the truss becomes more like a neuro-muscular system than a robotic variable geometry truss.

As mentioned above, GSFC researchers are studying the NBF-based approach to achieving a synthesis of low- and high-level approaches to robotic control.

For large numbers of components, such as the thousands of nodes in the PAM solar sail or even more in pseudo-continuous articulated matter, the individual nodes and groups of them must essentially be autonomous systems and their control must be handled by a scalable, distributed control system that limits and moderates the information flow between the lowest level and the heuristic level. This is one of the key motivations behind the eminently scalable Evolvable Neural Interface that is the key innovation of the NBF architecture. The scalability of the NBF Synthetic Neural System underlies the control architecture of the Autonomous Nano-Technology Swarm (ANTS) mission architecture. It is designed to be self-similar so that the same control architecture can be used at the various levels of the system and sub-systems.

Teleoperation At this point we may note that ART and SMART trusses need not be controlled only by autonomous robotic means, but are also quite amenable to teleoperation. In fact, it may even be possible to develop ART/SMART technology for use in prosthetic devices and other spinoff opportunities where a self-reconfigurable or remotely controlled structural material might be applied. For example, haptic interfaces could naturally be implemented using ART/SMART trusses providing a means for computer interaction, input and output, using the sense of touch or physical manipulation.

CONCLUSION

In this paper, we have discussed a technological pathway being pursued at NASA Goddard Space Flight Center. ART and its descendant SMART are ways to construct variable geometry meshes that provide a new structural material that we are applying to aerospace systems. The first prototypes involve planetary rovers that can flow over planetary terrain carrying embedded science instrument packages embedded within their reconfigurable truss work. A range of applications have been considered ranging from heavy duty, robust ART trusses capable of moving boulders and regolith around on the Moon to high performance Gossamer solar sails for PAM spacecraft making a resource map of the asteroids. ART and SMART architectures may be developed using many kinds of actuation and structural technologies: for the smallest scale SMART fabrication the truss will look like ordinary continuous matter. The issue of developing a scalable control system that can be distributed across the vast number of degrees of freedom helping the autonomous control of these systems was discussed.

In the near term, ART structures, thanks to advances in computation and communication, opens up the possibility for dramatic new deployable concepts and reconfigurable structures. The architecture is fundamentally undifferentiated, it can be made or formed into a variety of structural elements, and moreover it can be reconfigured or actively change or move as well. In the long term, ART/SMART architecture may change the way we think of solid structural materials and the things we build from them.

ACKNOWLEDGMENTS

Support for this work has been provided by NASA's Revolutionary Aerospace Systems Concepts program through NASA contract NNG04EE43D and NAS5-99189, subcontract 0299189EER, with ITMI. Support by NASA/GSFC Internal Research & Development and the Director's Discretionary Fund is also acknowledged. Technologies discussed in this work are subject to provisional patent applications.[5]

REFERENCES

The project website for this work is *ants.gsfc.nasa.gov*.

[1]Curtis, S.A., et al, "Neural Basis Function Control of Super Micro Autonomous Reconfigurable Technology (SMART) Nano-Systems," *in the Proceedings of the First AIAA Intelligent Systems Technical Conference*, Chicago 20-22 September 2004.

[2]NASA Goddard Space Flight Center Prov. patent applications GSFC 14657, 14762, 14763, 14764, 14848, 14849, 14850, 14858, and 14859.

[3]Hasslacher, B. and M. W. Tilden, "Living Machines," *Robotics and Autonomous Systems: The Biology and Technology of Intelligent Autonomous Agents*. Editor: L. Steels. Elsevier Publishers, Spring 1995. (LAUR - 94 - 2636)

[4]Cheung, C.Y. et al, "Intelligent Systems in the Evolvable ANTS Architecture," *in the Proceedings of the First AIAA Intelligent Systems Technical Conference*, Chicago 20-22 September 2004.

[5]Clark, P.E., et al, "LARA: Near Term Reconfigurable concepts and components for lunar exploration and exploitation," IAF, 55th Congress, IAC-04-IAA.3.8.1.08, IAC Proceedings, October 2004.

[6]Rilee, M.L. et al, "Solar sail implementation using SMART matter," IAF, 55th Congress, IAC-04-S.6.07, October 2004

[7]Clark, P.E. et al, "BEES for ANTS: Space Mission Applications for the Autonomous Nano-Technology Swarm," *in the Proceedings of the First AIAA Intelligent Systems Technical Conference*, Chicago 20-22 September 2004.

[8]Clark, P.E. et al, "PAM: Biologically inspired engineering and exploration mission concept, components, and requirements for asteroid population survey," IAF, 55th Congress, IAC-04-Q5.07, IAC Proceedings, October 2004.

[9]Curtis, S.A. et al, "ANTS (Autonomous Nano-Technology Swarm): An Artificial Intelligence Approach to Asteroid Belt Resource Exploration," IAF, 51st Congress, October 2000.

[10]Miura and Furya, "Adaptive structure concept for future space applications," AIAA Journal, Vol. 26, No. 8, 1988; among others referred to in Wada, B. and Das, A. "Selected Papers on Smart Structures for Spacecraft," SPIE Milestones Series, Vol. MS167.